

DOCUMENT RESUME

ED 309 078

SE 050 733

AUTHOR Lavoie, Derrick R.
TITLE Effects of Prior Knowledge and Piagetian Cognitive Development on the Process Skill of Prediction in the Learning Cycle.
PUB DATE 89
NOTE 31p.
PUB TYPE Reports - Research/Technical (143)

EDRS PRICE MF01/PC02 Plus Postage.
DESCRIPTORS Cognitive Development; Computer Simulation; High Schools; *Learning Processes; *Piagetian Theory; *Prediction; *Prior Learning; *Problem Solving; Science Instruction; *Secondary School Science
IDENTIFIERS *Process Skills; Science Education Research

ABSTRACT

This study examined the science process skill of prediction problem solving using naturalistic research methodology and information-processing theory. The think-aloud interview led to the identification of several specific program exploration and prediction behaviors. A total of 14 high school biology students made predictions concerning the effects of the independent variables upon dependent variables through time using a computer simulation on water pollution. Students were identified according to initial knowledge of the subject matter and success at solving three selected prediction problems. Successful predictors generally had high initial knowledge of the subject matter and were formal. Unsuccessful predictors generally had low initial knowledge of the subject matter and were concrete. High initial knowledge seemed to be more important to predictive success than stage of Piagetian cognitive development. Behavioral tendencies between successful and unsuccessful predictors over all stages of the learning sequence and between stage one and stage three predictions were compared. Implications for problem-solving theory, cognitive development, and science teaching were discussed. (Author/YP)

* Reproductions supplied by EDRS are the best that can be made *
* from the original document. *

ED309078

EFFECTS OF PRIOR KNOWLEDGE AND PIAGETIAN COGNITIVE DEVELOPMENT
ON THE PROCESS SKILL OF PREDICTION IN THE LEARNING CYCLE

U. S. DEPARTMENT OF EDUCATION
Office of Educational Research and Improvement
EDUCATIONAL RESOURCES INFORMATION
CENTER (ERIC)

☒ This document has been reproduced as
received from the person or organization
originating it.

☐ Minor changes have been made to improve
reproduction quality.

• Points of view or opinions stated in this docu-
ment do not necessarily represent official
OERI position or policy.

"PERMISSION TO REPRODUCE THIS
MATERIAL HAS BEEN GRANTED BY

Derrick R. Lavoie

Derrick R. Lavoie
College of Education
Science Education
Wayne State University
Detroit, Michigan 48202

TO THE EDUCATIONAL RESOURCES
INFORMATION CENTER (ERIC)."

SE 050 733

Abstract

Science process skills are the primary tools facilitating scientific problem solving, a fundamental goal for our largely inadequate educational system. In general, there is lack of research and understanding concerned with how students acquire and use science process skills to solve problems.

This study examines the science process skill of prediction problem solving, in detail, using naturalistic research methodology and information-processing theory. The think-aloud interview, modeled after Ericsson and Simon (1984), led to the identification of several specific program exploration and prediction behaviors. Systematic comparative analyses were performed on student behaviors associated with different comparison groups (e.g., concrete versus formal operational, unsuccessful versus successful predictors, low versus high-initial knowledge of the subject matter).

High school biology students made predictions concerning the effects of the independent variables upon dependent variables through time using a computer simulation on water pollution. Students were identified according to initial knowledge of the subject matter and success at solving three selected prediction problems.

Successful predictors generally had high initial knowledge of the subject matter and were formal. Unsuccessful predictors generally had low initial knowledge of the subject matter and were concrete. High initial knowledge seemed to be more important to predictive success than stage of Piagetian cognitive development.

The results of this study have implications for problem-solving theory, cognitive development, and science teaching. Knowledge of cognitive behaviors may help the teacher understand student's conceptions about a system and guide subsequent instruction and questioning.

INTRODUCTION

An essential goal of our schools is to help create a scientifically literate nation with an intelligent population that can think critically to solve everyday life's problems as well as deal with rising societal and environmental concerns. A national study of our nation's schools revealed that most students do not develop any of the abilities commonly listed under "intellectual development": the ability to think rationally, the ability to use and evaluate information to solve problems, curiosity, creativity or the desire and ability to pursue further knowledge (Goodlad, 1983). The National Assessment of Educational Progress reveals extremely high percentages of students in science lack the ability to apply, analyze and intergrate scientific information and procedures (Mullis and Jenkins, 1988).

It is imperative that we end the widespread scientific illiteracy and improve science process and problem solving skills for our nation's youth (Bennett, 1988). Science process skills, which include such operations as hypothesizing, inferring, analyzing, experimenting, and predicting, are critical skills for scientific problem solving (Gagne, 1965; Doran, 1978). Consequently, the development of teaching methodologies that effectively teach process/problem-solving skills has become a goal for both science education research (Linn, 1987) and curriculum development (National Commission on Excellence in Education, 1983). It is also the broad goal of this research study.

In order to learn and/or teach a skill, one must first identify and master each of its associated subskills. The inter-relationships between the variables affecting performance of these subskills must also be understood. Solving problems is cognitive skill that involves performing many thinking behaviors, or subskills, in certain patterns and sequences to arrive at a solution. Many variables may affect problem solving success. Thus, it is the assumption of this research study that the detailed mechanisms of thinking involved with process/problem solving skills process must first be understood, as well as the associated affecting variables, before productive teaching methodologies can be developed. It is also the assumption of this study that process/problem solving skills can best be taught if they are incorporated into an effective model of learning.

Thus, the purpose of this research study is to understand some of the more probable components affecting with the process skill of prediction as part of an effective learning model. The components addressed include subject's initial knowledge of the subject matter, Piagetian cognitive development, and the thinking behaviors involved with making predictions. The effective model, to be used as a vehicle for prediction, is the learning cycle. The rationale for these facets of the research study are discussed below.

Prediction

Prediction problem solving is recognized as an essential component of scientific inquiry and is a terminal objective for science education research (Butts et al., 1978). It involves thinking components such as observation and pattern identification (McGalliad and Cooney, 1979), inferring rules (Thiel and George, 1976), and synthesizing and evaluating data (McAulay and Camelio,

1976). It is clear that the skill of prediction is fundamental to the progress, learning, and instruction of science (Good and Lavoie, 1986). Extensive literature review revealed a paucity of science education studies dealing with the thinking mechanisms, teaching, and assessment of prediction.

Learning Cycle

Robert Karplus (1977) and others developed a three-phase learning cycle based on the application of Piaget's work to science education. It involves phases of initial exploration, followed by concept introduction, and then concept application.

During the exploratory phase the student interacts with a new situation with minimal guidance or demand from the teacher. The purpose: to present the student with mental complexities which s/he cannot resolve. In Piagetian terms, this should raise questions, result in disequilibrium, and set the stage for self-regulation. In the second phase, concept introduction, a new concept or principle is presented to the student via lecture, film, text, etc. This step should allow students to apply the new concepts or reasoning patterns to their initial experiences. This provides for Piagetian social transmission and further aids self-regulation. In the last phase, concept application, students apply their new concepts to additional situations.

It is well documented that instruction based on the Karplus learning cycle improves conceptual understanding when compared to traditional instruction (Abraham & Renner, 1986). Therefore, it would seem productive to combine the model with the process skill of prediction.

Prediction and the Learning Cycle

Prediction can be added to the learning cycle to give it greater flexibility and instructional power. It also makes the cycle more congruous with the information-processing paradigm of cognitive science and the nature of science, per se. Good and Lavoie (1986) suggest that prediction be added at the beginning of the learning cycle with feedback loops among the four main components (Figure 1). Feedback loops will make the cycle more flexible and diminish the impression that the progression is strictly linear. Good and Lavoie (1986) further suggest that making prediction an essential part of this learning cycle provides the student and teacher with the following advantages:

- 1). Students will be encouraged to organize existing knowledge.
- 2). Students will become more aware of the diversity of opinions held by peers.
- 3). There will be greater commitment of students to follow up on their efforts.
- 4). Teachers can use students' predictions to aid in assessment of their understandings.
- 5). Predictions can be used as a type of pretest by which to judge initial understanding and later progress.

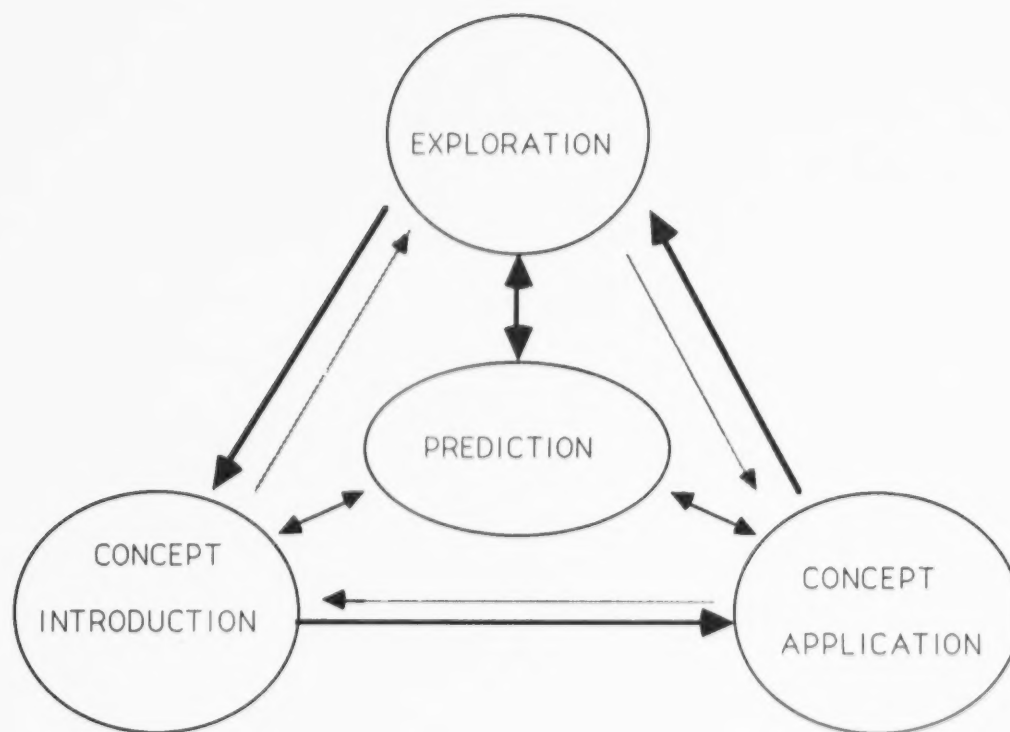


Figure 1. Flexible learning cycle with "prediction power"
(from Good and Lavoie, 1986)

Initial Knowledge of the Subject

Both declarative (subject matter) and procedural (skill or process) knowledge are essential to solving problems (Larkin et al., 1980). The quantity (amount) and quality (organization) of each type knowledge are additional factors that can result in successful or unsuccessful predictions. To more fully understand the prediction process it will be useful to identify the amount and organization of both procedural and declarative knowledge.

Piagetian Cognitive Development

Piagetian cognitive developmental theory has proven useful to elucidating the underlying structures or schema of the mind (Inhelder and Piaget, 1958). As the mind "learns," the schema change to become more organized and integrated. The presence and absence of given schema lead to classification of an individual at a given stage of cognitive development. Perhaps, certain schema are more useful than others to making successful predictions? Thus, it may be possible to gain insight into the thinking processes involved with making predictions through the application of Piagetian theory.

Thinking Processes

In recent years, the information processing paradigm has been recognized to hold promise for research in science education directed toward discovering and describing the mechanisms by which people perform thinking tasks (Larkin, 1982; Stewart and Atkin, 1982; Larkin and Rainard, 1984; Good, et al., 1986). In broad terms, information processing theory seeks to explain the processes of thinking associated with the brain's input and output of information. The human cognitive process is viewed as a sequence of internal states which are serially transformed by a sequence of information processes. Consequently, information processing theory serves as the framework for this research which aspires to describe the cognitive processes and pathways associated with prediction.

OBJECTIVES

The above rationale gives impetus to this study whose general purpose is to describe and understand, in detail, the mechanism of thought associated with making predictions and its relationship to subject's initial knowledge and cognitive development. This involves the cognitive behaviors associated with how a water pollution system is explored by students using a computer simulation program, and how predictions are subsequently made about the system. The specific objectives of the qualitative-based study are to:

1. Determine subject's thought processes or behaviors associated with program exploration and predictions following stage one and stage three of a modified Karplus learning cycle.
2. Determine how subjects' thought processes or behaviors of program exploration and prediction are affected by their initial knowledge of the subject matter.

3. Determine how subjects' cognitive behaviors of prediction are affected by their stage of Piagetian cognitive development.
4. Determine how subjects' behaviors of prediction vary relative to their success or lack of success at making predictions.

METHODOLOGY

Naturalistic qualitative research methods have recently been recognized in the science education literature as a very useful research tools (Stake and Easley, 1978; Smith, 1982; Easley, 1982; Rist; 1982; Welch, 1983). Two research techniques from this methodology were employed to investigate the prediction process and to identify subjects for this study: the Piagetian clinical interview and the "think aloud" interview, respectively.

One high achieving and one low achieving subject were theoretically sampled (Bogdan and Taylor, 1975) so as to provide maximum variability for an initial pilot study. Following this, randomly administered Piagetian interviews assessing formal schema of proportions, combinations, and probability, identified six concrete and six formal operational Biology I and II high school students. The Piagetian interviews were also administered to the pilot subjects. Pilot subject No. 1, the low achiever, was found to be concrete operational. Pilot subject No. 2, the high achiever, was found to be formal operational. Table I shows subject background information indicating age, sex, grade point average, and national science and math percentiles achieved in March 1985 on the Comprehensive Test of Basic Skills (MacGraw Hill, 1983).

The "frog problem" was used to assess the schema of ratio and proportion (Violino and DiGiacomo, 1981). An electrical switch box consisting of a light and four switches (DeLuca, 1977) was used to assess combinatorial reasoning. Three separate tasks requiring the subject to predict the probability of drawing a given item from a group of colored objects of differing shapes were used to assess the formal schema of probability (Lawson, 1978). Overall, if the subject was labeled formal on all three schema s/he was identified as a "formal subject." If the subject was concrete on at least two of the schema, and formal on none, s/he was labeled concrete. For reasons of standardization, comparison, and compatibility of research, the Piagetian interview protocol was identical to that used by Smith (1983) except for the introductory remarks.

The prediction think-aloud interview involved approximately two hours of a three-stage instructional sequence in water pollution, similar to the one reported by Karplus (1977), but with opportunity for prediction added. To provide data concerning the processes of thought involved with making predictions each subject was asked to verbalize his/her reasoning or thoughts (i.e., to think aloud). This was done while the subject answered preliminary questions about the subject matter, explored a computer simulation and conducted preset exercises involving the computer simulation, and while s/he made predictions concerning the system of study. The interviewer tried not to suggest any responses to the subject. When the subject failed

Table I. Subject Background Information Including Age, Sex, Grade Point Average, and CTBS Math and Science National Percentiles.

Subject	Age	Sex	GPA	CTBS Math	CTBS Science
No. 1	18	male	1.59	68%	13%
No. 2	16	male	3.96	97%	99%
No. 3	17	female	2.80	76%	84%
No. 4	16	male	3.11	98%	99%
No. 5	17	female	1.85	59%	73%
No. 6	17	male	2.04	76%	56%
No. 7	16	female	3.76	96%	96%
No. 8	17	male	3.93	96%	99%
No. 9	17	female	2.06	44%	65%
No. 10	17	female	2.54	48%	41%
No. 11	15	male	1.94	99%	97%
No. 12	16	male	3.31	92%	87%
No. 13	17	female	4.00	99%	95%
No. 14	15	female	3.77	96%	74%

Note. CTBS = Comprehensive Test of Basic Skills; GPA = grade point average.

to respond for greater than five seconds s/he was encouraged to think aloud. If a subject became disoriented or strayed from the problem s/he was prompted to return to and remain on task. To retain data in permanent original form the entire interview sequence was videotaped. The initial pilot study with one concrete and one formal subject provided evidence that the methodology was sound and useful to learning about the prediction process.

Subject Matter

Predictions can be made about any dynamic system (physical or biological) involving several variables which affect the system. The subject matter chosen for this study deals with one such system, water pollution. This involved written material (readings and exercises) and a computer simulation program, "Pollute", published by Educational Materials and Equipment Company. The "Pollute" program allows the user to rapidly manipulate five independent variables (temperature, waste type, dumping rate, type of treatment, and the type of body of water) that affect water quality. The pollution effect is displayed on a color plot simulating the change of two dependent variables, oxygen and waste concentration, through time for a specified number of days. The simulated oxygen curve may continue straight across the graph or slope downward to eventually level off or reach zero. The simulated waste curve may continue straight across or slope upward to eventually level off.

Instructional Sequence

During stage one subjects were asked preliminary questions to assess their understanding of water pollution. They were then given approximately 15 minutes to explore the computer simulation. Paper and pencil were provided for the purpose of taking notes if a subject so desired.

Following the exploration, subjects were given three written prediction problems, asked to read each aloud, and to illustrate each of their predictions on blank graph sheets with specified variables listed on the side. The prediction problems consisted of two parts, A and B. In part A, a situation involving different parameters of the five independent variables served as the problem about which the subjects made predictions. In part B, the parameters of one or two independent variables were changed, and again the subjects made predictions.

Stage two involved having each subject read background information on water pollution that described some of the effects or relationships between the independent and dependent variables, as well as details about given independent variables.

In stage three, subjects worked through several exercises with the computer program designed to illustrate some of the relationships and concepts they were exposed to during stage two. This involved inputting pre-selected parameters and observing several simulation runs that illustrated how the dependent variables changed over a range of values of a given dependent variable. Subjects recorded the results of each simulation run on data sheets, and commented on how the dependent variables were affected by the independent variables. Following this each subject was asked to solve the same three prediction problems as given at stage one.

Analysis

Common behaviors were identified from the video taped prediction interviews using guidelines from Ericsson and Simon (1984) and Smith (1983). Initially, the two pilot subjects were studied and a list of behaviors for program exploration and prediction was developed. The twelve study tapes were then reviewed and the list modified to include additional behaviors. Based on this review by the principal author and co-analysis by the second author, the behaviors were deemed satisfactory for analysis, hypothesis construction, and drawing conclusions. The procedure resulted in a final list of 63 cognitive process behaviors associated with program exploration and prediction. Qualitative data analysis of the video tapes involved the techniques of verbal protocol analysis (Ericsson and Simon, 1984) and "comparative systematic analysis" (Glaser and Strauss, 1967). Encoded transcripts were made of the sequential occurrences of each behavior for program exploration, stage-one predictions, and stage-three predictions for each subject. The total numbers of each behavior for program exploration, stage-one and stage-three predictions were tallied for each subject.

The comparative systematic data analysis of this study consisted of the identification of differences and similarities in the coded behaviors of program exploration, stage-one prediction, and stage-three prediction. Comparisons were made relative to two-category combinations of the following comparison groups: successful versus unsuccessful predictors, concrete versus formal subjects, low initial-knowledge versus high initial-knowledge subjects, and stage-one predictions versus stage-three predictions. Low, moderate, and high initial-knowledge subjects were identified according to how well they answered a set of preliminary questions about water pollution. Successful, transitional, and unsuccessful subjects were distinguished relative to their illustrated predictive accuracy and logical reasoning.

Analysis of each comparison group involved indentifying high, low, and moderate behavioral tendencies for each comparison category. A category was considered to have a high tendency to exhibit a given behavior if the average number of occurrences of the behavior per subject was greater than or equal to 70%. This percentage was based on comparison with the average number of occurrences of the behavior per subject of the opposing category group. If the average number of occurrences of the behavior per subject was less than or equal to 30% it was considered to have a low tendency for a given category. Behaviors which occurred greater than 30% but less than 70% were considered common to both categories, and to have a moderate or common tendency.

RESULTS

The results of this study are presented in relation to: 1) global trends observed between the comparison groups particularly in regard to Piagetian cognitive development and initial knowledge of the subject matter, 2) behavioral tendencies observed between the comparison groups, and 3) verbatim examples illustrating some of the behaviors are provided.

Global Trends

Piagetian stage, initial knowledge level, and predictive success at stage one and three are given for each subject in Table II. By comparing Table I with Table II it can be noticed that successful predicting subjects tended to have high or moderate initial-knowledge, formal thinking ability, and high academic achievement. Unsuccessful predicting subjects tended to have low initial knowledge, concrete thinking ability, and low academic achievement. Subject No. 14, who had high initial knowledge, was a high achiever and a successful predictor, but who was concrete operational, did not follow this trend.

Thus, it would appear that cognitive development and initial knowledge of the subject matter are factors that may account for a subject's predictive success. Further, at least in the case of subject No. 14, initial knowledge of the subject matter appears more important to predictive success than Piagetian cognitive development.

In general, there was an increase in number of successful subjects and a decrease in number of unsuccessful subjects from stage one to stage three. This suggests that learning took place between stage one predictions and stage three predictions which allowed subjects to make more successful predictions.

Successful subjects showed greater persistence and motivation during program exploration and solving of the prediction problems than did unsuccessful subjects. For example, successful subjects performed, on average, 50% more simulation runs, tended to take notes, and seemed more interested in learning about water pollution than the unsuccessful subjects. Some successful subjects found the learning sequence stimulating and enjoyable, and they spent much more time contemplating and evaluating their predictions than did unsuccessful subjects.

In contrast, although all subjects completed the learning sequence, the unsuccessful subjects expressed dissatisfaction and lack of interest at various stages, usually towards the end of the sequence. For example, some showed reluctance when given the last set of prediction problems, while others found the exercises too long.

Behavioral Tendencies

Behavioral tendencies were determined for successful versus unsuccessful, formal versus concrete, and low initial versus high initial knowledge comparison groups. It was found that the successful, formal, and high initial-knowledge subjects shared many of the same behavioral tendencies. Likewise, unsuccessful, concrete, and low initial-knowledge subjects shared many of the same behavioral tendencies. These results are explainable, in part, by the fact that many of the same subjects that were successful were formal and had high initial knowledge, and that many of the same subjects that were unsuccessful were concrete and had low initial knowledge.

Behavioral tendencies for successful versus unsuccessful subjects are summarized, in no particular order, in Table III. It is important to note that while each subject of each category did not exhibit every type of behavior, overall there was a high tendency to either exhibit or not to exhibit the behavior. That is, the

Table II. Summary of Results for Individual Subjects
Indicating Piagetian Cognitive Stage, Initial Knowledge
Level, and Predictive Success at Stages One and Three.

Subject	Piagetian Stage	Init. Kn. Level	Predictive Success	
			Stage 1	Stage 3
No. 1	Concrete	Moderate	T	T
No. 2	Formal	Moderate	T	T
No. 3	Concrete	Moderate	U	U
No. 4	Formal	High	T	S
No. 5	Concrete	Low	U	U
No. 6	Concrete	Moderate	U	T
No. 7	Formal	High	T	T
No. 8	Formal	Moderate	S	S
No. 9	Concrete	Low	U	T
No. 10	Concrete	Low	U	U
No. 11	Formal	Moderate	S	T
No. 12	Formal	Moderate	T	S
No. 13	Formal	High	T	S
No. 14	Concrete	High	T	S

Note. Init. Kn. = initial knowledge; U = unsuccessful;
T = transitional; S = successful.

Table III. Summary of Contrasting Behavioral Tendencies
Between Successful and Unsuccessful Predictors Over All
Stages of the Learning Sequence.

=====	=====
Successful Subjects Tended	Unsuccessful Subjects Tended
-----	-----
1. to develop and use a qualitative scale which designated conditions of the dependent and independent variables (e.g. low, moderate, high).	1. to not use a descriptive qualitative scale.
2. to explore the program in a systematic way (e.g. change only one independent variable at a time for a given simulation run.	2. to explore the program in a non-systematic way (e.g. change several independent variables at a time).
3. to return manipulated independent variables to a base line condition (i.e. the default values) in order to maintain a more consistent base of comparison for identifying effects.	3. to not return manipulated independent variables to base line.
4. to wonder about, try to find, identify, and use a greater number of correct independent-dependent variable bi-directional relationships.	4. to wonder about, try to find, identify, and use a greater number of non-directional and incorrect bi-directional relationships.
5. to wonder about, try to find, identify, and use ratio relationships (i.e. relationships based on quantitative comparisons over a range of independent-dependent relationships).	5. to not wonder about, try to find, identify, and use ratio relationships.
6. to look for the best and worst conditions for the dependent variables during program explorations.	6. to not look for the best and worst conditions.
7. to exhibit less misconceptions about the subject.	7. to exhibit a greater number of misconceptions about the subject.
8. to not make mistakes in reading the graphs.	8. to make more errors in reading the graphs.

Table III--Continued

=====	=====
Successful Subjects Tended	Unsuccessful Subjects Tended
-----	-----
9. to predict how a given independent variable will relate to a given dependent variable during program exploration, test out the relationship, and then judge the predictive success.	9. to not make predictions that are then tested and judged.
10. to take notes during program exploration.	10. to not take notes during program exploration.
11. to understand the directions and information given during the lesson.	11. to misunderstand the directions and information given
12. to plan future action during program exploration	12. to not plan future action during program exploration.
13. to identify the important independent variable factors (i.e. those that affect the dependent variable).	13. to not identify the important independent variable factors.
14. to recognize a balance between the effect of two independent variables relative to their effect on a dependent variable.	14. to not recognize a balance.
15. to rely on information learned in the lesson to make predictions, etc.	15. to rely on information not learned in the lesson (i.e., to draw from previous knowledge bases) to make predictions.
16. to provide supporting data for a stated reason, relationship, prediction, etc. (i.e., does not guess).	16. to not provide any supporting data (i.e., guess).
17. to recognize and correct own errors made during predicting, identifying relationships, etc.	17. to not recognize and correct own errors made during predicting, identifying relationships, etc.
18. to average a number of mini-predictions that were made based on one independent variable to make a final prediction.	18. to not average mini-predictions to make a final prediction.

Table III--continued

=====	=====
Successful Subjects Tended	Unsuccessful Subjects Tended
-----	-----
19. to hypothesize or predict a relationship in order to make a prediction.	19. to not hypothesize a relationship in order to make a prediction.
20. to use similar conditions found in the exercises or notes that have been modified based on independent-variable relationships to make predictions.	20. to use the same conditions found in the notes or exercises that have not been modified to make predictions.
21. to reach general conclusions.	21. to not reach general conclusions.
22. to show greater persistence and motivation to complete the learning sequence.	22. to show less persistence and motivation to complete the learning sequence.

number of occurrences of a given behavior per subject (averaged over all subjects of that category) was greater than or equal to 70%, or less than or equal to 30%. Thus, behaviors in Table III can be considered typical of subjects in the unsuccessful or successful category.

Successful subjects tended to use behaviors that were systematic and required more abstract reasoning. For example, they tended to explore systematically, predict and identify bi-directional and ratio relationships, plan, test, judge, and reach conclusions.

To make accurate predictions in this study it was important to know the relationship between the dependent and independent variable relative to the direction of change. Subject's predictions were most accurate if they involved both the direction and magnitude of change. Four types of relationships were distinguishable in this study. Non-directional relationships involved noting that one independent variable affected a dependent variable, but not saying how (e.g., temperature affects oxygen). Directional relationships involved the direct effect of one independent variable upon a dependent variable (e.g. high temperature means low oxygen). Bi-directional relationships are more dynamic. Their identification depended upon comparison of the range of values for one independent variable values with the range of a dependent variable (e.g., as the temperature increases the oxygen decreases; or waste is unaffected by changes in temperature). Ratio relationships, the most useful to making accurate predictions, required quantitative thinking over a range of independent-dependent variable relationships (e.g. for every rise of temperature of one degree, the oxygen decreases 3 ppm).

It should be mentioned that taking notes facilitated identification of relationships by allowing comparisons to be made between several computer runs without having to rely on memory. However, this was not prerequisite to success. Subject No. 8, for example, had an excellent memory and by recalling correct bi-directional relationships identified during exploration was able to make accurate predictions at stage one.

Unsuccessful subjects tended to be non-systematic, less abstract, and to not use many of the behaviors characteristic of successful subjects. For example, they tended to have more misconceptions and misunderstandings related to the subject matter, to make more errors, and to apply knowledge of non-directional and incorrect bi-directional relationships.

Contrasting behavioral tendencies between stage one and stage three were noted over all subjects and are summarized in Table IV. Notice that at stage three the subjects tended to use more lesson-related (i.e. relevant) information. This apparently led to the identification and use of more relationships, and to finding supporting reasons for predictions. Consequently, they also had fewer mistakes, knowledge gaps, and misconceptions. It is reasonable to conclude that these changes in behavioral tendencies between stage one and stage three are largely responsible for increases in predictive success at stage three for all category groups. The subjects having access to background information on water pollution and completing exercise data tables dealing with the effect of ranges of the independent variables on the dependent variable are probable factors accounting for the above behavioral changes.

Table IV. Summary of Contrasting Behavioral Tendencies
Between Stage One and Stage Three Predictions.

Stage One Predictors Tended:	Stage Three Predictors Tended:
1. To make unsupported predictions (i.e., to guess.	1. To use or find a supporting reason.
2. To use notes to aid in making predictions.	2. To use exercises to aid aid in making predictions.
3. To identify more knowledge gaps	3. To identify fewer knowledge gaps.
4. To rely on information not learned in the lesson.	4. To rely on information learned in the lesson.
5. To make more mistakes in reading the graphs, and, consequently more corrections.	5. To make fewer mistakes in reading the graphs, and consequently less corrections.
6. To find and use fewer relationships to make a smaller number of successful predictions.	6. To find and use more relationships to make a greater number of successful predictions.
7. To rely more on memory.	7. To rely less on memory.
8. To express greater doubt and confusion.	8. To express less doubt and confusion.
9. To have more misconceptions	9. To have fewer misconceptions.

Examples

Selected verbatim examples illustrating some of the more interesting behavioral tendencies in Table III have been chosen to give the reader an understanding for how the raw data led to the qualitative results of this study. Comments are included with each behavioral transcript taken while subjects explored the program or made predictions at stage one or stage three.

Non-Systematic and Systematic Variable Manipulation--One of the primary differences between successful and unsuccessful subjects was how the independent variables (temperature, dumping rate, etc.) were manipulated during program exploration for each simulation run. Unsuccessful subjects tended to non-systematically manipulate or change several independent variables at a time for single simulation runs:

No. 3: OK (enters variables). I will change it to lake, a low temperature of 5 degrees, make it (waste type) sewage, change it (dumping rate) to 10, and make treatment primary. (Subjects observes the simulation, and states observation.) The oxygen went down and the waste stayed the same. (Records the results of the simulation run in numerical form.)

Notice that subject No. 3 manipulated four independent variables at a time (unsuccessful behavior 2, Table III), did not identify any relationships (unsuccessful behavior 4, Table III), and gave a rather vague description of how oxygen changed through time (unsuccessful behavior 1). Not manipulating one independent variable at a time over a range of values made it impossible to identify a true relationship between a given independent variable and the dependent variable.

Successful subjects tended to be systematic in their manipulation of the independent variables during program exploration. The identification of correct bi-directional relationships, in addition to ratio relationships (behaviors 4 and 5, Table III) were characteristic of successful predictors.

No. 8: I want to see what the temperature does, so I'll work with just it, and keep all the other values the same. (Changes temperature to 10 degrees and observes simulation run.) It doesn't seem to change. Let's change the value to the highest and see if it makes a difference (changes and observes). So, temperature does make a difference. The higher the temperature the lower the oxygen level, and the temperature does not affect the change in waste. (Subject identifies two correct bi-directional relationships.)

Notice that subject No. 8 was aware of using the highest and lowest values (behavior 1, Table III) to see extreme effects, which seemed to help in identifying correct relationships. The importance of relationship knowledge is further shown in the next few examples.

Use of Incorrect Relationships--In the following example only one variable has been changed and the subject must predict based on this change. Subject No. 10's use of an incorrect relationship led to an inaccurate prediction.

(Prediction three, Part B)

No. 10: I'm trying to remember which kind of treatment was best (non-directional relationship)...I think it was the primary that was the best (incorrect relationship). So, I'll put waste lower.

Notice that subject No. 10 knew that the treatment had an effect (non-directional relationship) but incorrectly thought that primary treatment was better than secondary treatment, and thus, incorrectly put waste lower rather than higher (unsuccessful behavior 4, Table III). In this case, knowledge of only two bi-directional relationships would have been sufficient to make the correct changes to the dependent variables to result in successful predictions.

Use of Ratio Relationships.-- As discussed previously the use of correct bidirectional are very important for making accurate predictions. In the following example subject No. 8 compared independent variables in the student exercise data tables and identified variables in the student exercise data tables and identified two ratio relationships relative to waste concentration. The subject then compared them to a highly accurate prediction, finding that one relationship far outweighed the other.

No. 8: The waste level is going to come down from what it was (in part A) even though the ppm (dumping rate) was increased. Because, the increase in waste was about twice with the increase in dumping from 3 ppm to 7 ppm (refers to exercise data table 4). But, the secondary waste treatment (refers to exercise data table 2) reduced the waste to $1/16$ of what it was with the primary treatment. So, With a difference of $1/2$ compared to $1/16$, secondary treatment would probably bring, whatever the value of the dumping rate, the waste to near zero.

By relying on information in the exercise data tables to identify and compare two relevant ratio relationships, subject No. 8 was able to make a prediction almost exactly like that of the actual computer simulation. Subject No. 8's high aptitude in math (see CTBS math score, Table 1) may be a factor that influenced his ability to think quantitatively and identify ratio relationships.

It should be pointed out that there was more than one strategy that led to successful or unsuccessful prediction. For example, one successful strategy employed by subject No. 13 involved averaging the results of several minipredictions to arrive at an overall prediction. Each miniprediction was based on correct directional and bidirectional relationships of each independent variable taken in turn until all were examined. A typical unsuccessful strategy was to use nondirectional relationships to make unsuccessful predictions. Since direction and magnitude are not known with a nondirectional relationship, it was necessary to guess. Such guesses were often inaccurate.

In sum, successful prediction depends on knowledge of correct bidirectional and ratio relationships, in addition to strategic knowledge of how to apply those relationships in given prediction problem situations. Further, more than one strategy may be used to make accurate predictions.

CONCLUSIONS AND DISCUSSION

The primary goal of this study was to examine, in detail, the science process skill of prediction using information-processing theory and naturalistic research methods. Throughout the learning sequence the interview procedures, modeled after Ericsson and Simon (1984), encouraged the subjects to think aloud. This technique led to the identification of 63 program exploration and prediction behaviors associated with the water pollution system. Comparative systematic analyses (Glaser and Strauss, 1967) of identified behavioral tendencies within and between the following comparison groups were then performed: successful versus unsuccessful predictors, formal versus concrete subjects, low initial-knowledge versus high initial-knowledge subjects, and stage one versus stage three predictions.

The large number of program exploration and prediction behaviors identified from the data led to a number of conclusions concerning behavioral tendencies, Piagetian cognitive development, and initial knowledge of the subject matter. In addition, this discovery-oriented study led to conclusions concerning the use of the computer simulation and motivation. The implications for theory and teaching are discussed below. As well, several recommendations are made concerning future research.

It should be noted that, in general, there was high similarity between the successful, formal, and high initial-knowledge subjects, and between the unsuccessful, concrete, and low initial-knowledge subjects. The principle reason for this result was that many of the same subjects fell into the successful, formal, and high initial-knowledge categories. Thus, the conclusions reached about successful subjects generally pertain to high initial-knowledge and formal operational subjects. Also, the conclusions reached about unsuccessful subjects generally pertain to low initial-knowledge and concrete subjects. However, some interesting and unexpected anomalies occurred relative to these conclusions.

Behavioral Tendencies

The think-aloud technique resulted in a unique base of behavioral patterns and tendencies concerning the science process skill of prediction. Major differences in cognitive strategies were found between successful and unsuccessful subjects as they explored the computer simulation and made predictions. Many of the behaviors, with slight modifications, could apply to almost any science system dealing with variables that have an effect on other variables. The think-aloud interview has not only increased knowledge of prediction but of problem solving in general.

Prediction problem-solving success, as defined by the criteria of this study, can be considered a continuum of different unique behaviors and varying behavioral tendencies. Subjects at the extremes of this continuum are clearly distinguishable, particularly in relation to the types of unique behaviors and the average number of occurrences of given behaviors per subject. For example, a successful subject at one extreme might identify and use five bi-directional relationships, one for each of the five independent

variables, to modify the dependent variable and make an accurate prediction. At the other extreme, an unsuccessful subject might identify at most one non-directional relationship, and then not be able to apply it in a prediction situation. Smith and Good (1984), who compared experts and novices, found a similar continuum for genetic problem-solving success.

Successful subjects tended to explore the program variables systematically (i.e., by manipulating only one independent variable at a time per simulation run). This behavior was necessary to identify bi-directional and ratio relationships which were shown to be very important to successful prediction in this study. This seems related to the Piagetian schema of isolation and control of variables. The schema can be tested by the "bending rods task" (Lawson, 1979) which asks subjects to identify variables and the effect of each one on a dependent variable (i.e., the amount of bending of a rod). Lawson (1979) found a close relationship between isolation and control of variables and combinatorial reasoning. It is not surprising the unsuccessful subjects, who could not systematically manipulate variables, were concrete operational on the combinations task.

In sum, successful prediction strategies seem to involve two basic knowledge components: 1) knowledge of correct bi-directional and/or ratio relationships, and 2) knowledge of how to apply the relationships in given problem situations to make accurate predictions. As well, predictive success in this study was a continuum of the degree of "closeness" between the subject's prediction and that of the actual computer simulated prediction. In very few cases was any subject's prediction nearly identical to the computer-simulated prediction. When it was, the use of ratio relationships were usually involved.

The fact that the quality of predictions made about the system generally improved between stage one and stage three of the learning sequence suggests that learning occurred. It seems probable some useful information about relationships, reasons, reading the graphs, etc. was acquired about the variables from reading the text material and working through the exercises which led to more accurate predictions. The greater use of relationships, supporting reasons, information in the text, and exercise data tables, as well as fewer misconceptions, knowledge gaps, and confusion at stage three compared to stage one supports this conclusion (see Table IV).

It is also possible that making predictions at stage one may have served as a type of "advance organizer" as Good and Lavoie (1986) explicitly suggest, and some of the related literature implicitly suggest (Frase, 1968; Mayer, 1977). This may have enhanced the learning that subsequently occurred during stage two by focusing subjects' attention upon relevant information (e.g., relevant relationships) which would have allowed them to make more accurate predictions. Supporting evidence is shown by the high tendency of the successful subjects compared to the unsuccessful subjects to access relevant information in the text (see Table IV). while making stage three predictions. Lastly, giving the identical prediction problems at stage three, as well as the preliminary questions at stage one, may have further served to focus attention on important information.

Cognitive Development

Predictive success was found to be related Piagetian cognitive development. This conclusion agrees with several research studies which found relationships between Piagetian cognitive development and science process skill (Linn and Their, 1975; Boyer and Linn, 1978; Padilla, 1980).

It should be mentioned that in the case of subject No. 14, who had high initial knowledge but was concrete, high initial knowledge seems to be more important to predictive success than cognitive development. This conclusion agrees with Smith (1983), who found that Piagetian cognitive development was not crucial to problem-solving success. However, it is important to recognize that subject No. 14 may have been formal operational on the three tasks tested for, but still failed to provide "acceptable" answers. If so, subject No. 14 would be an example of the "false negative", a possibility that needs to be considered in any research employing Piagetian tasks.

But, if subject No. 14 was truly concrete, and not a "false negative," then at least three possibilities exist. First, formal operational thought is not necessary for solving the prediction problems of this study. Second, the prediction process is dependent on formal thinking, but not relative to the three Piagetian tasks of this study. Subject No. 14, may have been formal on other tasks necessary to make accurate predictions. Third, the relationship between science process skills and formal operational thought may be more tentative than previously thought.

Of these possibilities, the second one seems the most likely. Subject No 14's high tendency to systematically manipulate the independent variables during program exploration suggests that she was formal at isolating and controlling variables, which is one schema of formal thought (Lawson, 1979). Lawson (1979; p. 67) states, "The generation of all possible combinations of variables, the isolation and control of variables, and the solution of problems of proportionality all theoretically require formal operations." Lawson (1979) tested the Piagetian hypothesis that performance on all three of these tasks is dependent upon a set of unified cognitive operations, such that, individuals who have acquired these unified operations should perform consistently on all three task. He found "substantial" correlation among the three tasks which supported his hypothesis. The results of subject No. 14, who appears to be formal on isolation and control of variables but was found to be concrete on combining variables, is evidence against this hypothesis. However, when all concrete subjects of this study are taken into account over all simulation runs there is a high tendency for them to non-systematically manipulate the independent water pollution variables.

Thus, the results of this study relative to Piagetian stages of cognitive development generally support the Piagetian hypothesis of unified cognitive operations and agree with the Lawson study.

Implications for teaching

The findings of this study relative to cognitive development imply there will be students of varied cognitive development and

predictive ability in any one class. This must be considered when developing curriculum, teaching approaches, etc. Lawson (1979) makes the following recommendation for high school instruction relative to cognitive development that applies to this dissertation:

Any one secondary school teacher will likely be faced with such wide range of student competence that teaching a course designed for any one level would be inappropriate. A possible solution to this problem is to teach the course around relatively open-ended laboratory [or prediction] activities that inherently allow for varying levels of student involvement. (p. 71)

Initial Knowledge

Predictive success was related to initial knowledge of the subject matter. High initial-knowledge subjects showed greater prediction improvement at stage three than low initial-knowledge subjects. High initial knowledge may have helped subjects focus attention on relevant relationships, integrate the material into existing conceptions, and enhance meaningful learning.

It is important to note that cognitive development relative to this study does not seem to offer as much substantive support for the differences between successful and unsuccessful subjects as does initial knowledge which is consonant with the information-processing view. Considerable related research has also shown this to be true for problem solving, in general (Ausubel, 1968; Simon, 1980; Mayer, 1983; Smith, 1983). Information-processing theory places emphasis on the amount, organization, and accessibility of knowledge in long term memory as responsible for differences in problem-solving success. The success of concrete subject No. 14 could then be attributed to her amount of knowledge about water pollution as well as her ability to use that knowledge to solve the prediction problems.

Thus, this study implies, as does problem-solving theory, that knowledge of the subject matter (i.e. declarative knowledge) in addition to knowledge of how to apply that knowledge (i.e., process or procedural knowledge) is important to problem-solving success. Larkin (1979) comments on the interrelatedness of these two types of knowledge (cited in Smith, 1983):

Procedural knowledge cannot be considered in isolation from the knowledge structures on which processes must operate....Because solution of complex problems generally requires knowledge of the world, the amount, accuracy, and organization of an individual's knowledge must influence the effectiveness of problem-solving efforts. (p. 72)

Simon (1981) also recognizes these two components relative to information-processing theory. He addresses the importance of the quantity of knowledge stored in LTM to problem solving success, as well as how that knowledge is indexed and organized (which affects its accessibility).

Implications for Teaching

The obvious implication for teaching the science process skill

of prediction that arises from the above is that: science teaching strategies should focus on better ways to increase both declarative and procedural knowledge. One way to do this is to develop and teach science courses based on a problem-solving approach. The problem-solving approach used extensively in math education, has been argued for in general education (Tuma and Reif, 1980) and science education (Lawson, 1982; Smith, 1985). Fisher and Lipson (1983) provide several techniques for developing problem-solving teaching methods. Interestingly, research on teaching procedural knowledge necessary to solve problems indicates that giving facts or lists of appropriate behaviors to perform is ineffective (Larkin, 1980). Larkin (1980) found procedural knowledge is better taught by, "Providing explicit instruction in functional procedural units....which make available coherently bits of information that are often used together" (p. 121). Further, she found that this is facilitated by instruction based on hierarchical rather than linear sequential organization. One result of hierarchical instruction using functional procedural units is an increase in problem-solving performance (Larkin, 1980). Additionally, instructional designs which first teach students to execute simple actions and then to focus on ways to guide the selection and application of these actions may prove effective (Landa, 1976).

To develop teaching strategies following these guidelines science educators need to become familiar with the associated behaviors and cognitive pathways of prediction. After identifying a student's unsuccessful and successful behaviors, successful behaviors could be encouraged and unsuccessful behaviors discouraged. This might involve helping students to identify subject related knowledge and then to apply relevant information (e.g., knowledge of correct bi-directional relationships) in different prediction problem situations. Thus, teachers need to assist students in developing both content as well as process knowledge.

Considerable problem-solving research has been devoted to delineating general problem-solving heuristics (Rubinstein, 1974). The steps used to summarize the prediction process (i.e., identifying and applying relationships to make a prediction) suggest possible prediction problem-solving heuristics. For example, one heuristic might involve identifying bi-directional relationships and averaging the effects of each one together in sequence. This heuristic would probably be specific to a prediction situation involving several variables over measurable ranges of change which affect changes in a dependent variable over time. Content knowledge thus becomes important to the degree that it helps identify the relevant relationships involved. An extreme case of this heuristic would be the prediction equation used in the "Pollute" simulation program to model the dependent variable changes over time. The parameters of the prediction heuristic or formula (i.e., the relationships) would obviously need to be changed for each subject matter domain. This conclusion further emphasizes the importance of both procedural and declarative knowledge.

Computer Simulation

The computer simulation program proved to be an effective tool. The computer simulation allowed subjects to rapidly determine the effects of several independent variables upon the dependent

variables. Such effects would have taken weeks to determine through field studies. The immediate feedback given by the computer may have facilitated storage in subject's long-term memory of the associations between the independent variable changes and the effects to the dependent variables (i.e., relationships). Subject No. 8's ability to remember correct relationships during stage one may be an example of this effect.

It should also be mentioned that the computer simulation may have served a similar role as that of a hands-on laboratory. The keyboard became the instruments or tools to be used in variable manipulation and data collection, and the computer screen became the eye through which to observe experimental effects.

Motivation

This research found motivation and persistence to affect the behaviors responsible for prediction problem-solving success. For example, lack of motivation of unsuccessful subjects may explain why they tended to: 1) be more confused and give responses with little thought or reason, 2) not wonder about effects or relationships, 3) not take notes, etc. (see Table III). Smith (1983) identified motivation as a necessary component of problem-solving theory, "which most researchers have only recently attempted to include in their theories" (p. 241). Smith and Good (1984), who discuss motivation as factor in genetic problem solving success, point out that "motivation may be more a result than a cause...success at problem solving may result in higher motivation which may, in turn, lead to more study and success, etc." Teachers need to continually be looking for, testing, and evaluating ways to increase the motivation of their students.

It should be mentioned that use of the computer simulation program was probably not a major factor affecting subjects' motivation. Many of the subjects chosen had worked extensively with computers previously. This decreased the novelty, which otherwise would probably have acted to increase interest and motivation.

Future Research

This research has led to several conclusions which offer viable ground for future research studies employing both psychometric and naturalistic methodologies.

Future research is needed to further identify the effects of initial knowledge and cognitive development on prediction success. Subjects who are identified as concrete operational and having high initial knowledge of the subject matter could be the focus of such a study. Also, research investigating the effects of procedural knowledge relative to declarative prediction knowledge could have application for science process skill instruction, information-processing theory, and computer modeling.

Motivation was shown to be important and is worthy of future investigation. A study identifying factors affecting motivation of selected groups of subjects solving different kinds of problems would be useful to developing techniques for increasing this affective attribute. In addition, the results could be used to increase

problem-solving success and develop problem-solving theory.

In information-processing terms, motivation affects the amount of information encoded in LTM by facilitating the rate of transfer of that information from STM to LTM (Anderson, 1986). Anderson (1986) has recently developed a neuromathematical model of information processing which considers the effects of motivation on rate and amount of information in a learning task. However, before the effects of motivation can be studied in different learning situations future research is needed to develop instruments that can validly and reliably measure it. Anderson (1986) recognizes that the task of measuring motivation is "made more complex by the need to specify whether one is seeking to assess general motivational states or motivation relative to a particular task."

Effective ways of teaching and evaluating prediction need to be developed. This may involve testing various types of teaching strategies, learning sequences, and instructional materials designed to optimally organize and store both procedural and declarative knowledge in LTM. Any evaluative instrument would ideally need to test both declarative and procedural knowledge. Perhaps, such an instrument could be developed from the behavioral tendencies identified in Table III.

The three-phase Karplus learning cycle developed for Science Curriculum Improvement Study has been shown to have many advantages over traditional instruction (Abraham and Renner, 1986). The learning cycle approach used with this study increased predictive success between phase one and phase three. Future research is necessary to further investigate the role of prediction relative to the three-phase learning cycle. Questions should be considered relative to the effects of incorporating prediction into the learning cycle at various points and in conjunction with other subject matter domains on student attitudes, predictive success, content acquisition, and conceptual learning.

Lastly, the use of a computer simulation in this study appeared to greatly facilitate subjects' manipulation of variables and subsequent observation of results. Future research is needed to explore the effectiveness of computer simulated laboratory situations and scientific phenomenon. A recent article suggests that research on computers in science learning should address the following questions which are applicable to this study:

What are the interactions between computer graphics and learner variables? What do students really observe when they work at a vide screen? What connections do they make between their observations and the worlds of theory and reality? What kinds of software are appropriate for students who have learned how to control variables? In what ways can software [simulations] promote the development of logical structures like the ability to control variables? (Kracjik, Simmons, and Lunetta, 1986, p. 469).

In sum, this naturalistic research study involved an in-depth observation and analysis of the science process skill of prediction. It provides several implications for related theory and pedagogy, and serves as an important source of future research questions.

REFERENCES

- Abraham, M. R. & Renner, J. W. (1986). The sequence of learning cycle activities in high school chemistry. Journal of Research in Science Teaching, 23(2), 121-144.
- Anderson, R. O. (1986). Studies on information processing rates in science learning and related cognitive variables 1: Some theoretical issues related to motivation. Journal of Research in Science Teaching, 23(1), 61-66.
- Ausubel, D. (1968). Educational psychology. New York, NY: Holt, Rinehart, & Winston.
- Bennett, W. J. (1988). American education: Making it work. Washington, D.C.: U.S. Government Printing Office.
- Bogdan, R., & Taylor, S. J. (1975). Introduction to research methods. New York, NY: John Wiley & Sons.
- Boyer, J., & Linn, M. (1978). Effectiveness of Science Curriculum Improvement Study in teaching scientific literacy. Journal of Research in Science Teaching, 15, 209-219.
- Butts, D., Capie, W., Fuller, E., May, D., Okey, & Yeany, R. (1978). Priorities for research in science education. Journal of Research in Science Teaching, 15(2), 109-114.
- DeLuca, F. P. (1977). Measurement of logical thinking: An electronic equivalent of Piaget's first chemical experiment. Journal of Research in Science Teaching, 14(6), 539-544.
- Doran, R. L. (1978). Measuring the "processes of science" objectives. Science Education, 62(1), 19-30.
- Easley, J. A., Jr. (1982). Naturalistic case studies exploring social-cognitive mechanisms and some methodological issues in research on problems of teachers. Journal of Research in Science Teaching, 19(3), 191-203.
- Ericsson, K. & Simon, H. A. (1984). Protocol analysis: Verbal reports as data. Cambridge, MA: MIT Press.
- Fisher, K. M., & Lipson, J. I. (1983). Information processing interpretations of errors in college science and mathematics learning. Davis, CA: University of California Press.
- Frase, L. T. (1968). Some data concerning the mathemagenic hypothesis. American Educational Research Journal, 5, 181-189.
- Gagne, R. (1965). The psychological issues in Science-A-Process-Approach. Washington, D.C.: American Association for the Advancement of Science.
- Glaser, B. G., & Strauss, A. L. (1967). The discovery of

grounded theory: Strategies for qualitative research.
New York, NY: Aldine Publishing Co.

- Good, R., Kromhout, R., & Bandler, W. (1986). Human and machine diagnosis of scientific problem-solving abilities. Journal of Research in Science Teaching, 23(4), 263-275.
- Good, R., & Lavoie, D. (1986). The importance of prediction in a science learning cycle. Florida Association of Science Teachers' Journal, 1(4), 24-35.
- Goodlad, J. I. (1983). A place called school: Prospects for the future. New York: McGraw-Hill Book Co.
- Inhelder, B. & Piaget, J. (1958). The growth of logical thinking. New York, N.Y.: Basic Books.
- Karplus, R. (1977). Science teaching and the development of reasoning. Journal of Research in Science Teaching, 14(2), 169-175.
- Kracjik, J. S, Simmons, P. E., & Lunetta. (1986). Improving research on computers in science learning. Journal of Research in Science Teaching, 23(5), 465-470.
- Landa, L. N. (1976). Instructional regulation and control. Englewood Cliffs, NJ: Educational Technology.
- Larkin, J. H. (1979). Processing information for effective problem solving. Engineering Education, 70, 285-288.
- Larkin, J. H. (1980). Teaching problem solving in physics: the psychological laboratory and the practical classroom. In D. T. Tuma & F. Reif (Eds.), Problem solving and education: Issues in teaching and research. Hillsdale, NJ: Lawrence Erlbaum Assoc.
- Larkin, J. H. (1982). Studying how people think: An application in the science classroom. In R. E. Yager (Ed.), What research says to the science teacher (Vol. 4, pp. 22-30). Washington, DC: National Science Teachers Association.
- Larkin, J. H., & Rainard, B. (1984). A research methodology for studying how people think. Journal of Research in Science Teaching, 21(3), 235-254.
- Lawson, A. E. (1978). The development and validation of a classroom test of formal reasoning. Journal of Research in Science Teaching, 15, 11-24.
- Lawson, A. E. (1979). Combining variables, controlling variables, and proportions: is there a psychological link? Science Education, 63(1), 67-72.
- Linn, M., & Their, H. (1975). The effect of experiential science on the development of logical thinking in children. Journal of Research in Science Teaching, 12,

- Mayer, R. E. (1977). The sequencing of instruction and the concept of assimilation to schema. Instructional Science, 6, 369-388.
- McAulay, J. D. & Camelio, F. (1976). The process of prediction for sixth graders. Clearing House, 49(8), 346-348.
- McGalliad, W. & Cooney, T. J. (1979). Inferring and predicting--some activities. School Science and Mathematics, 79(8), 602-606.
- Mullis, I. V. S. & Jenkins L. B. (1988). The science report card: Elements of risk and recovery. Princeton, N.J.: Educational Testing Service.
- National Commission on Excellence in Education. (1983). A Nation at risk: The imperative for educational reform. Washington, DC: U.S. Government Printing Office.
- Padilla, M. J. (1980). Science activities--for thinking. School Science and Math, 80, 601-608.
- Rist, R. C. (1982). On the application of ethnographic inquiry to education: Procedures and possibilities. Journal of Research in Science Teaching, 19(6), 439-450.
- Rubinstein, M. F. (1974). Patterns of problem solving. Englewood Cliffs, NJ: Prentice-Hall.
- Simon, H. A. (1980). Information-processing explanations of understandings. In P. W. Jusezyk, & R. M. Klein (Eds.), The nature of thought: Essays in honor of D. O. Hebb. Hillsdale, NJ: Lawrence Erlbaum Associates.
- Simon, H. A. (1981). Cognitive science: The newest science of the artificial. In D. A. Norman (Ed.), Perspectives on cognitive science. Norwood, NJ: Abbex.
- Smith, M. L. (1982). Benefits of naturalistic methods in research in science education. Journal of Research in Science Teaching, 19(8), 627-638.
- Smith, M. U. (1983). A comparative analysis of the performance of experts and novices while solving selected classical genetics problems. Dissertation Abstracts International, 44, 451A. (University Microfilms No. 8314200)
- Smith, M. U. (1985). Classroom-tested recommendations for teaching problem solving within a traditional college course: Genetics. Paper presented at the annual meeting of the International Society for Individualized Instruction, October, Newark, NJ.

- Smith, M., & Good, R. (1984). Problem solving and classical genetics: Successful vs. unsuccessful performance. Journal of Research in Science Teaching, 21, 895-912.
- Stake, R. E., & Easley, J. A. (1978). Case studies in science education. Urbana, Ill: Center for Instructional Research and Curriculum Evaluation.
- Stewart, J. H., & Atkin, J. A. (1982). Information processing psychology: A promising paradigm for research in science teaching. Journal of Research in Science Teaching, 19, 321-322.
- Thiel, R. P., & George, K. D. (1976). Some factors affecting the use of the science process skill of prediction by elementary children. Journal of Research in Science Teaching, 13(2), 155-166.
- Tuma, D. T., & Reif, F. (1984). Problem solving and education: Issues in teaching and research. Hillsdale, NJ: Lawrence Erlbaum Assoc.
- Violino, P., & DiGiacomo, B. S. (1981). An investigation of Piagetian stages in Italian secondary school students. Journal of Chemical Education, 58, 639-641.
- Welch, W. W. (1981). Inquiry in school science. In N. C. Harms, & R. E. Yager (Eds.), What research says to the science teacher (Vol. 3, pp. 53-72). Washington, DC: National Science Teachers Association.
- Welch, W. W. (1983). Experimental inquiry and naturalistic inquiry: An evaluation. Journal of Research in Science Teaching, 20(2), 95-103.